MSc in Photonics

PHOTONICS**BCN**

Universitat Politècnica de Catalunya (UPC)
Universitat Autònoma de Barcelona (UAB)
Universitat de Barcelona (UB)
Institut de Ciències Fotòniques (ICFO)

http://www.photonicsbcn.eu

Master in Photonics

MASTER THESIS WORK

OPTICAL TESTING AND CLINICAL APPLICATIONS OF ABERRATION-FREE INTRAOCULAR LENSES

Sara Pastor Fabregat

Supervised by Dr. Chris C. Hull, (City University London) and Montserrat Arjona (UPC)

Presented on date 9th September 2010

Registered at

Escola Tècnica Superior d'Enginyeria de Telecomunicació de Barcelona

Optical testing and clinical applications of aberration-free intraocular lenses.

Sara Pastor Fabregat
Department of Optometry & Visual Science, City University London, Northampton Square, London EC1V 0HB, UK

E-mail: sarapastor2@gmail.com

Abstract. The spherical aberration of an Akreos ADAPT AO aberration-free intraocular lens was studied using a point-diffraction interferometer and the ocular aberrations of patients undergoing pre-operative assessment for implantation with this lens were obtained with a Scheimpflug system (Pentacam) and Hartmann-Shack aberrometer (Zywave). Measured values for the Z(4,0) coefficient were 0.028 µm +/- 0.019 and 0.021 µm +/- 0.013 for the Akreos lens and an equivalent spherically-surfaced intraocular lens when measured in air with a collimated beam at 543.1nm. Anterior and posterior corneal aberrations on 11 subjects demonstrated that the posterior cornea contributed 1.2 times the spherical aberration of the anterior surface of the cornea. In addition, lenticular spherical aberration values were found to be -1.543 µm +/- 0.29 when corneal aberration data was combined with whole eye aberrometry. In air interferometry did not demonstrate lower values of spherical aberration for the aspheric Akreos lens as expected. This may have been due to liquid film effects on the surfaces negating the aspheric profile. Point-diffraction interferometry was found to be limited in the amount of tilt that could be produced to generate tilt fringes for analysis. The corneal posterior surface spherical aberration is not negligible and should be taken into account when designing and selecting aspheric intraocular lenses. Customized intraocular lenses would provide the optimal result for all patients.

Keywords: Aspheric intraocular lenses, spherical aberration, wavefront aberrometry, cornea, crystalline.

1. Introduction

Modern cataract surgery not only aims to replace the opacified crystalline lens with an artificial transparent lens but also to optimise the quality of vision of the patients. Wavefront sensing technology has provided the tool to measure the ocular aberrations of eyes and hence provide the data required to design aspheric intraocular lenses which can alter the higher-order aberrations as well as correct sphere and cylinder.

Our eyes are not a perfect, diffraction-limited optical system and like all the imperfect systems they have optical aberrations. The total aberration of the eye is given by the sum of corneal aberrations and lenticular aberrations[1]. The spherical aberration (SA) of the cornea is approximately stable with age[2] with both anterior[2] and posterior[3] surfaces of the cornea showing a slight increase in positive spherical aberration. In contrast lenticular SA becomes significantly more positive with age[4]. In young crystalline lenses negative SA compensates the positive SA of the cornea[5], but in older eyes the SA of the crystalline lens becomes more positive adding to the corneal SA. The balance of spherical aberration between the cornea and lens therefore reduces with age[4].

The contribution of the posterior surface of the cornea to the total corneal spherical aberration has been studied since it is relevant to interpreting results from different methods used to determine corneal aberrations (videokeratoscopy – anterior surface; scanning slit/Scheimpflug – both anterior and posterior). Some studies have found the contribution of the posterior surface to the total aberration of the cornea to be within the measurement error[6] while Sicam *et al* [3] found that the measurement of the anterior surface only may lead to an error in the calculation of SA from -8% to 27%[3] and Piñero *et al* [22] reported primary spherical aberration of posterior surface of the cornea to be 114% greater than the SA of the anterior surface of the cornea. This suggests that total corneal spherical aberration needs to be considered when designing IOLs that alter the whole eye spherical aberration.
Spherically-surfaced IOLs have positive spherical aberration adding to the positive SA of the cornea in a fashion similar to an older crystalline lens. However, aspheric IOLs can be designed to produce different amounts of both positive and negative as well as zero spherical aberration by having anterior, posterior or both surfaces aspheric. A number of studies have compared the performance of spherical-surfaced IOLs with negative spherical aberration IOLs designed to compensate the positive SA of the average cornea[7-11]. The studies that tested best corrected visual acuity did not find a statistically significant difference between the two lenses[10, 11]. However it has been reported that aspheric IOLs provide better contrast sensitivity (CS) than spherical IOLs at frequencies such as 3, 6, 12 and 18 cycles per degree (cpd) under mesopic conditions and 12 and 18 cpd under photopic conditions particularly at larger pupil sizes[10, 11]. For aspheric IOLs with negative SA there is some data to support a loss of visual benefit when decentration is more than 0.4mm and tilt is greater than 7 degrees[12]. For these values of tilt and decentration their performance becomes equivalent to that of a spherical IOL. However, the presence of spherical aberration can increase the depth of focus leading to better distance-corrected near and intermediate visual acuity[13, 14, 8] by creating between 0.46 D[14] and 1 D[13] of pseudoacommodation. This suggests there may be some advantage in using positive spherical aberration IOLs. The design of aspheric IOLs has evolved to "aberration neutral" lenses that introduce zero spherical aberration leaving the eye with its corneal SA. Johanssonn *et al* [15] compared aspheric IOLs with negative SA and zero (neutral) SA and showed that both lenses gave similar high and low contrast visual acuities as well as photopic and mesopic contrast sensitivities. Eyes implanted with the negative SA aspheric IOL had less total high order aberrations (HOA) although 14% more of the patients preferred vision with the neutral aberration IOL. Moreover this type of aspheric lens is the safest option when post operation decentration and tilt are present[16] since they are more tolerant to these misalignments than the other types of IOLs. Consequently, neutral SA IOLs may have advantages over IOLs with other levels of spherical aberration when all factors are considered, they demonstrated less spherical aberration and better contrast sensitivity without scarifying tolerance to defocus.
One such lens is the Akreos AO (Advanced Optics Aspheric Lens) from Bausch & Lomb. It features an asymmetrical biconvex design with aspheric anterior and posterior surfaces that make the lens free from spherical aberration[18]. As a result, the pseudophakic eye is left with the amount of positive spherical aberration corresponding to corneal SA.
The aim of this study is to investigate the assumptions underlying the use of aberration-neutral IOLs. Specifically, we aim to develop optical test methods to determine the spherical aberration for the lens and discuss the expected change in spherical aberration. Secondly, Pentacam (Scheimpflug image) data of the cornea and whole eye aberrometry will be obtained to determine whether the Akreos lens will provide optical benefit in all eyes.

2. Methods

2.1. Experimental setup

The experimental set-up for optical testing is shown in figure 1. A green (543.1nm) He-Ne laser was expanded through a spatial filter and collimated using an aberration corrected doublet. A variable iris placed after the collimating lens controlled the beam diameter passing through the test lens. The test lens focused the laser beam on to the aperture of a Smartt point-diffraction interferometer. This is a common path interferometer where a small pinhole produces a spherical reference wavefront and a surrounding semi-transparent screen transmits the aberrated wavefront. The aberrated wavefront interferes with the spherical reference wavefront and the resulting interference fringes were captured with a DeltaPix Infinity X digital camera resolution 1280 x 1024 pixels. The interferometer was adjusted by first finding the best focus assessed visually by the least number of fringes present for a centred fringe pattern. Tilt fringes were then introduced using the x-y controls on the pinhols/screen of the point-diffraction interferometer (PDI) and a digital image of tilt fringes captured. The interferograms were analysed using a Fourier Transform method for fringe-pattern analysis[19] implemented in MatLab, which resulted in the wavefront and its corresponding Zernike coefficients. The software gave some negative values for Z(4,0), but since there was no analysis of phase shift all the results of SA were considered positive.

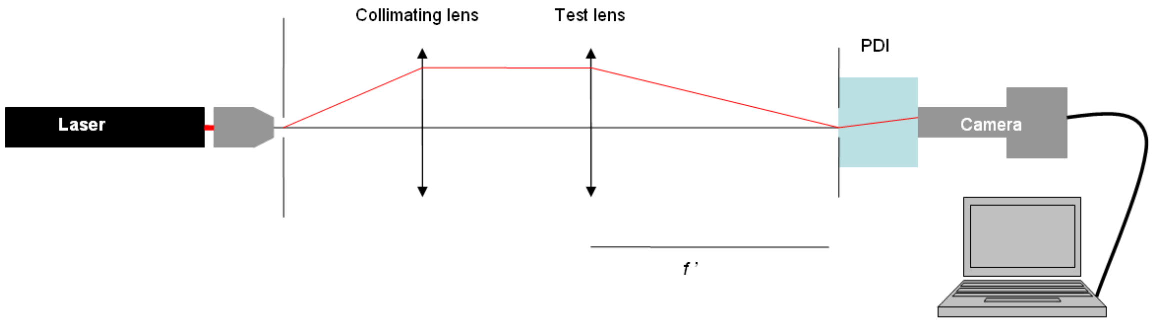

Figure 1. Lab setup

The method was validated by measuring an aberration-corrected Linos doublet of 100 mm of focal length and a plano-convex lens of the same power. The plano-surface of the plano-convex lens was facing the collimated beam thereby maximising the amount of spherical aberration. In contrast, the doublet was corrected for spherical aberration and coma and therefore should demonstrate significantly less spherical aberration. The lenses underwent the interferometric analysis as outlined above for a pupil diameter of 8 mm. To assess the accuracy the amount of SA for the Linos doublet was determined from the catalogue lens available in Zemax. The plano-convex lens was also modelled in Zemax having first determined its radii of curvature (Guild-Aldis spherometer), central thickness (digital micrometer), refractive index and Abbe number (Abbe Refractometer). Further, the analysis method was tested by reconstructing the interferogram from the wavefront data and carrying out a visual comparison against the original interferogram.
An Akreos Adapt AO aspheric IOL (power +21D) and a spherically-surfaced IOL (Acrysof SA65AT, Alcon; power +22D) were measured using the procedure outlined above but with the following minor modifications. The pupil diameter of the system was then 4 mm and the subjection of the Akreos was removed from solution prior to measurement since prolonged exposure in air would result in drying of the lens. The measurements were taken 12 times in order to have the mean and the standard deviation to see how reproducible the experiment was and to avoid imprecision in the position.

2.2. Patients measurements
Patient data was obtained from the cataract and clear lens surgery clinic at Moorfields Eye Hospital. Data were obtained on 11 eyes, (1 man and 5 women), with ages ranging between 47 and 68 years with a mean age 59.7 ± 7.9 years. There was no other comorbidity. Ethical approval and patient consent were not required since the data were obtained for audit purposes as part of the clinic's standard procedures.

Corneal aberrations were measured with a Pentacam (Oculus GmbH, Wetzlar, Germany) based on the Scheimpflug principle[20, 21]. It is a non-invasive system for measuring and characterising the anterior segment of the eye using a rotating Sceimpflug camera which takes images on the anterior and posterior corneal surfaces over a 180-degrees rotation. The elevation data from all these images are combined to form a three-dimensional reconstruction of the cornea. Corneal wavefront data are then derived by ray tracing[22, 23].
Total ocular aberrations were measured with a Hartman-Shack based aberrometer (Zywave, Baush & Lomb, Rochester, NY), Zywave aberrometry has been shown to have an acceptable repeatability estimating refractive error, as well as calculating Zernike terms of second-order and spherical aberrations[23]. Measurements with both instruments are centered on different axes of the cornea: the Pentacam is centred on the geometrical centre of the pupil[22] while aberrometer measurements follow the line of sight of the eye[24] which is defined by the point of fixation and the point of the cornea where the light coming from that point refracts to reach the fovea[25]. The measurement error caused by the different reference axes is reported to be insignificant and within the measurement error[3, 6].
All hyperopic patients and those who had a pupil size less than 6 mm under mesopic conditions were dilated with Tropicamide 1%. The scan was then carried out with patient's pupil size between 6 and 7 mm (if the natural pupil size was greater than 7 mm the level of light in the room was increased). To avoid accommodation during measurements the instruments have an internal test of fixation optically placed at the infinite[24].

3. Results

3.1. Results for the optical bench testing

Interferometric measurements of the aberration-corrected doublet and the plano-convex gave values for Z(4,0) of 0.00398 μm ± 0.0031 for the doublet and 0.019 μm ± 0.017 for the plano-convex lens. The reconstruction of the interferograms from the wavefront data was compared visually to the original interferograms and they were found to be similar. The Z(4,0) values obtained from Zemax in the same conditions of pupil diameter, wavelength and collimated beam was 0.000456 μm for the doublet and 0.01787 μm for the plano-convex lens.
The measurements with the intraocular lenses resulted as a Z(4,0) of 0.028 μm ± 0.019 for Akreos and 0.021 μm ± 0.013 for Acrysof. Belluci *et al*[26] reported a SA of near 0.035 μm for the Acrysof (SA60AT) lens.

3.2. Results from surgery patients

Table 1 shows the mean (± SD) of the corneal aberration data of both anterior and posterior surfaces obtained from subjects with Pentacam at 5 and 6 mm pupil.

Table 1. Values of spherical aberration for anterior and posterior surface of the cornea for different values of pupil size.

Patients age	Pupil size	Anterior surface SA	Posterior surface SA
59.67 ± 7.9	5 mm	0.4799 μm ± 0.15	0.3794 μm ± 0.24
59.67 ± 7.9	6 mm	0.7437 μm ± 0.24	0.6482 μm ± 0.31

Figure 2 shows the total corneal spherical aberration, corresponding to the sum of the spherical aberration of both surfaces of the cornea, anterior and posterior, against the age of the patients for both pupil sizes 5 and 6 mm. The correlation between age and corneal SA is 0.563.
And table 2 shows the SA for the crystalline of the eyes calculated by subtracting the total corneal aberrations (anterior and posterior) from the whole eye aberrations.

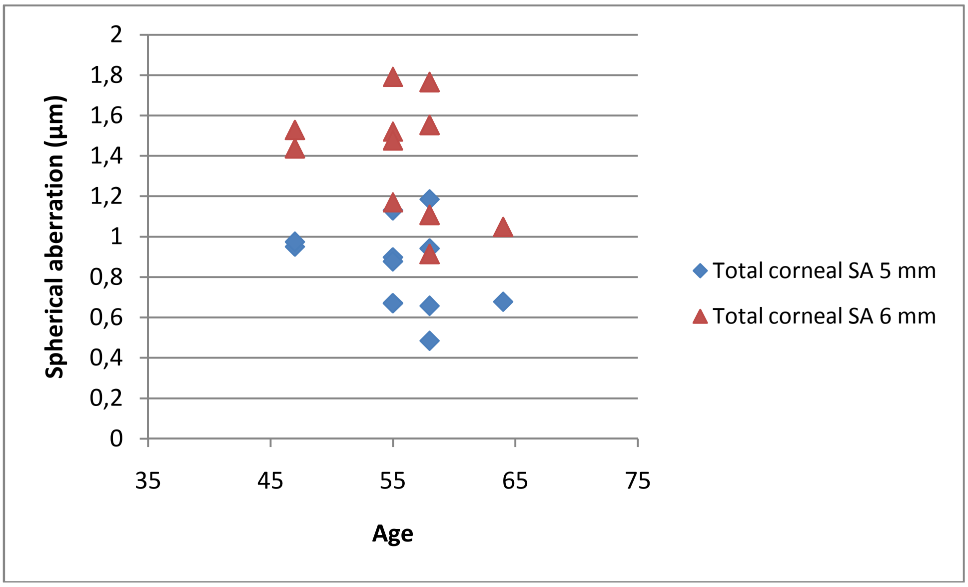

Figure 2. Values of total spherical aberration of the cornea as a function of age.

Table 2. Values of spherical aberration of the lens for different values of pupil size.

Patients age	Pupil size	Lens SA
59.67 ± 7.9	5 mm	-0.9195 μm ± 0.21
59.67 ± 7.9	6 mm	-1.5435 μm ± 0.29

4. Discussion

The results derived from the interferometric testing demonstrate significantly raised values of positive spherical aberration and no difference (within experimental error) between the spherical aberration of a spherically-surfaced IOL (SA65AT) and the Akreos SA neutral IOL. This was unexpected. One possible cause was the use of a collimated beam in air to test the lenses. The light that reaches the intraocular lenses placed in the eye is not a collimated beam but convergent, since it is refracted by the cornea. It is well known within optical design that spherical aberration changes with conjugates (object and corresponding image location). Also the lens in the eye is surrounded by aqueous and vitreous humour and not air as in the laboratory setup. The increase of power of the lens in air may lead to an increase on SA since it depends on surface power. To help investigate this further, Zemax was used to compare the spherical aberration values of the lenses designed to be in humours and illuminated with a convergent beam compared to those placed in air and illuminated with a collimated beam. The model demonstrated a higher amount of positive SA for both aspheric and spherical intraocular lenses in air and collimated light compared to the SA that they introduce in eyes. However, the model still predicted a significant difference between the spherical aberration of the two intraocular lenses. The model therefore does not explain why no difference in measured spherical aberration is found with interferometry between the two IOLs although it does explain why the aberration-neutral IOL has positive spherical aberration when measured in air with a collimated beam. A possible explanation for the lack of any reduction in measured spherical aberration for the Akreos IOL may be due to the fact that the Akreos lens is a foldable hydrophilic acrylic lens which is maintained in saline. It is probable that when the lens is removed to air for testing, the liquid will create a layer which may change the surface asphericity possibly negating the underlying surface asphericity designed to control spherical aberration. It is difficult to envisage how to overcome this although we have considered the use of an optical cuvette to contain the lens in saline. It would then be necessary to subtract the aberration inducing effects of the sides of the cuvette.

The Point Diffraction Interferometer (PDI) was also found to have some limitations. There is only a limited displacement of the pinhole/aperture needed to obtain tilt fringes necessary for analysis because the fringe contrast drops rapidly. A Twyman and Green interferometer, although it doesn't have the stability of a common-path configuration, has the advantages of more readily producing tilt fringes and also being able to phase shift the interferograms to obtain unambiguous signs to the aberration coefficients. Further development of this work should investigate this possibility.

The corneal spherical aberration measurements (Table 1) suggest that the second surface has significant SA, since it represents an average of the 56% of the total SA of the cornea. This is in agreement with Piñero *et al* who found it to be the 68%[22]. Both our results and those of Piñero *et al* contradict previous studies being significantly higher than the average of spherical aberration found in the anterior surface by Beiko *et al* of 0.27 μm for 6 mm pupil[27], or 0.28 μm found by Wang *et al*[28]. In addition the change of refractive index at the interface of the second corneal surface and aqueous humour is very small which means that the surface power and hence the contribuition to refraction and hence aberrations should be considerably smaller. The common point between this study and Piñero *et al* is the method of obtaining aberration data using the Pentacam Scheimpflug imaging system. Studies have reported on its repeatability and reproductivility for measurements such as the cornel thickness[29], but not in posterior corneal aberrometry. There is a need of further study on the differences of corneal aberrations obtained by Pentacam and other methods, especially regarding the software used for analysis. This is because Sicam *et al* used Scheimpflug camera and their own computational software for corneal aberration measurement and the resulting Z(4,0) values were in agreement with the previous literature on anterior corneal spherical aberration[3]. However, a significant contribuition from the posterior corneal surface suggests that both surfaces should be taken into account when describing eye aberrations and when corneal aberrations are used for the design of intraocular lenses. The focus on the anterior corneal surface could be due to the widespread use of videokeratoscopes that are now well developed and validated. Given the variability within the normal population, modelling IOLs with average parameters, as is done presently, may not always be appropriate and customized lenses are a possible solution.

In all subjects the amount of spherical aberration found in the crystalline lens was negative (table 2). Although other studies[30, 4] also found negative values of spherical aberration for the crystalline lens the amount of SA found in this study is larger than these studies. Smith *et al*[30] found the amount of spherical aberration in the crystalline for a group of subjects from 56 years to 72 years (mean age 69 years) to be 46.6% smaller than the SA obtained in the present study. This difference can be explained by the fact that the lens spherical aberration has been calculated by subtracting corneal aberrations from total aberrations. Since the measured values of the corneal aberrations are large as discussed above, the calculated aberrations for the crystalline lens will consequently be negative and higher.

The substitution of the crystalline lens in these patients with an intraocular lens with zero SA will lead to a total SA in the eye corresponding to the corneal spherical aberration, which is positive. This may cause some level of visual discomfort on these eyes because the pattern of aberrations of these patients will change radically from negative SA pre-operative to positive SA post-operative as the total eye aberrations will correspond only to the corneal contribution.

We were able to obtain post-operative measurements of corneal and whole eye aberrations using the same methods as for the pre-operative data on 1 patient. Corneal SA of 0.973 μm and whole eye SA of -0.18μm was found for 5 mm pupil. The result is surprising since it is expected that the whole eye and corneal spherical aberration values would be identical since the intraocular lens is "neutral". Although this is only on 1 subject, the masurements suggest that the implanted lens is producing negative SA and hence it is not acting as a neutral IOL. In clinical measurements the variation between subjects is usually very large, and for the eyes far from the average the aberration-free IOLs may not have the performance which they are designed for. This requires further investigation using a larger data set.

In summary, the point-diffraction interferometer has limitations when assessing intraocular lenses. Importantly, the level of tilt is limited by a fall in fringe contrast as the pinhole moves and phase shifting is difficult. Measurement of foldable lenses in air also presents probable difficulties due to the liquid film affect on the surface shape. A Twyman and Green interferometer with the lenses placed in an optical cuvette may help to overcome these limitations. Our aberrometry results indicate that posterior corneal surface aberration is significant and therefore should be taken into account. However, further investigation of the differences in assessing corneal surface shape by different measurement methods is required to explain the larger values obtained with Pentacam. The selection of the type of intraocular lens that is going to be implanted in a patient must be a careful process in which there are a large number of aspects to take into account, such as the use and the importance of pseudoaccommodation, the importance of contrast sensitivity, and the possible impact in subjective patients' vision.

Acknowledgments
My grateful thanks to my advisor, Prof. Chris C Hull for his help and encouragement throughout the course of this work and to Dr. Steve Gruppetta for his support in the computational part.

References

[1] El Hage S G and Berny F 1973 Contribuition of the crystalline lens to the spherical aberration of the eye *J. Opt. Soc. Am.* **63** 205-211
[2] Guirao A, Redondo M and Artal P 2000 Optical aberrations of the human cornea as a function of age *J. Opt. Soc. Am.* **17** 1697-1702
[3] Sicam V A, Dubbelman M and van der Heijde R 2006 Spherical aberrations of the anterior and posterior surfaces of the human cornea *J. Opt. Soc. Am.* **23** 544-549
[4] Artal P, Berrio E and Guirao A 2002 Contribution of the cornea and internal surfaces to the change of ocular aberrations with age *J. Opt. Soc. Am.* **19** 137-143
[5] Artal P, Guirao A, Berrio E and Williams D R 2001 Compensation of corneal aberration by the internal optics in the human eye *Journal of vision* **1** 1-8
[6] Barbero S, Marcos S and Merayo-Lloves J 2002 Corneal and total optical aberrations in a unilateral aphakic patient *J Cataract Refract Surg* **28** 1594-1600
[7] Montes-Mico R, Ferrer-Blasco T and Cervino A 2009 Analysis of the possible benefits of aspheric intraocular lenses: Review of literature *J Cataract Refract Surg* **35** 172-181
[8] Rocha K M, Soriano E, Chamon W, Chalita M R and Nose W 2007 Spherical aberration and depth of focus in eyes implanted with aspheric and spherical intraocular lenses *Ophthalmology* **114** 2050-2054
[9] Sandoval H P, Fernandez de Castro L E, Vroman D T and Solomon K D 2008 Comparison of visual outcomes, photopic contrast sensitivity, wavefront analysis, and patient satisfaction following cataract extraction and IOL implantation: aspheric vs spherical acrylic lenses *Eye* **22** 1469-1475
[10] Trueb P R, Albach C, Montes-Mico R and Ferrer-Blasco T 2009 Visual acuity and contrast sensitivity in eyes implanted with aspheric and spherical intraocular lenses *Ophthalmology* **116** 890-895
[11] Tzelikis P F, Akaishi L, Trindade F C and Boteon J E 2008 Spherical aberration and contrast sensitivity in eyes implanted with aspheric and spherical intraocular lenses: A comparative study *Am J Ophtalmol* **145** 827-833
[12] Holladay J T, Piers P A, Koranyi G, van der Mooren M and Norrby S 2002 A new intraocular lens design to reduce spherical aberration of pseudophakic eyes *J Refract Surg* **18** 683-692
[13] Marcos S, Barbero S and Jimenez-Alfaro I 2005 Optical Quality and depth-of-field of eyes implanted with aspheric and spherical intraocular lenses *J Refract Surg* **21** 1-13
[14] Nanavaty M A, Spalton D J, Boyce J, Saha S and Marshall J 2009 Wavefront aberrations, depth of focus, and contrast sensitivity with aspheric and spherical intraocular lenses: Fellow-eye study *J Cataract Refract Surg* **35** 663-671

[15] Johansson B, Sundelin S, Wikberg-Matsson A, Unsbo P and Behndig A 2007 Visual and optical performance of the Akreos Adapt Advanced Optics and Tecnis Z9000 intraocular lenses *J Cataract Refract Surg* **33** 1565-1572

[16] Pieh S, Fiala W, Malz A and Stork W 2009 In vitro Strehl ratios with spherical, aberration-free, average, and customized spherical aberration-correcting intraocular lenses *Investig Ophtalmol & Vis Scien* **50** 1264-1270

[17] Pepose S J, Qazi M A, Edwards K H, Sanderson J P and Sarver E J 2009 Comparision of contrast sensitivity, depth of field and ocular wavefront aberration in eyes with an IOL with zero versus positive spherical aberration *Graefes Arch Clin Exp Ophtalmol* **247** 965-973

[18] http://www.escrs.org/PUBLICATIONS/EUROTIMES/07/feb/pdf/AberrationfreeAkreos.pdf

[19] Takeda M, Ina H and Kobayashi S 1982 Fourier-transform method of fringes-pattern analysis for computer-based topography and interferometry *J. Opt. Soc. Am.* **72** 156-160

[20] http://www.pentacam.com

[21] http://www.trenholm.org/hmmerk/HMArtls.html

[22] Piñero D P, Alió J L, Alesón A, Escaf M and Miranda M 2009 Pentacam posterior and anterior corneal aberrations in normal and keratoconic eyes *Clin Exp Optom* **92** 297-303

[23] Dobos M J, Twa M D and Bullimore M A 2009 An evaluation of the Baush & Lomb Zywave aberrometer *Clin Exp Optom* **92** 238-245

[24] Rozema J J, Van Dyck D and Tassignon M J 2005 Clinical comparison of 6 aberrometers. Part 1: Technical specifications *J Cataract Refract Surg* **31** 1114-1127

[25] Mandell R B, Chiang C S and Klein S A 1995 Location of the major corneal reference points *Optom & Vis Sci* **72** 776-784

[26] Belluci R and Morselli S 2006 Are all spherical IOLs the same? *Cat & Refract Surg Tod* 56-60

[27] Beiko G H, Wolfgang H and Steinmueller A 2007 Distribution of corneal aspherical aberration in a comprehensive ophthalmology practice and wheter keratometry can predict aberration values *J Cataract Refract Surg* **33** 848-858

[28] Wang L, Dai E, Koch D and Nathoo A 2003 Optical aberrations of the human anterior cornea *J Cataract Refract Surg* **29** 1514-1521

[29] Barkana Y, Gerber Y, Elbaz U, Schwartz S, Ken-Dror G, Avni I and Zadok D 2005 Central corneal thickness measurement with the Pentacam scheimpflug system, optical low-coherence reflectometry pachymeter, and ultra-sound pachymeter. *J Cataract Refract Surg* **31** 1729-1735

[30] Smith G, Cox M J, Calver R and Garner L F 2001 The spherical aberration of the crystalline of the human eye *Vis Resear* **41** 235-243